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Stratigraphic and structural relationships across the Columbia River fault zone, Vernon and Lardeau map areas, British Columbia

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Abstract: The Columbia River fault zone in southern British Columbia has been interpreted as an Eocene crustal-scale detachment with tens of kilometres of hanging-wall displacement to the east. Along much of its length, it is defined by a shallow-dipping mylonite zone hundreds of metres thick. Field observations along Upper Arrow Lake, however, do not support the presence of a shallow-dipping detachment and show the existence of multiple, moderately to steeply dipping, brittle fault zones with limited displacement. The observed regional continuity of a Middle to Upper Paleozoic succession across the Columbia River fault zone is consistent with displacement of a few kilometres or less. This Paleozoic succession is lithologically distinct from the Lardeau and Milford groups east of the Kuskanax Batholith. The transition between the two successions could be a basinal hinge, the locus of depositional interfingering, or a fault of syndepositional or postdepositional origin.

Résumé : La zone de failles de Columbia River, dans le sud de la Colombie-Britannique, a été interprétée comme un décollement éocène d'échelle crustale caractérisé par l'affaissement,sur des dizaines de kilomètres, du compartiment supérieur à l'est. Sur la plus grande partie de sa longueur, cette structure est définie par la présence d'une zone de mylonite à faible pendage mesurant des centaines de mètres d'épaisseur. Des observations sur le terrain le long du lac Arrow supérieur n'appuient toutefois pas la présence d'un décollement à faible pendage; elles révèlent plutôt l'existence de zones de failles cassantes à pendage modéré à fort et à déplacement limité. La continuité régionale observée d'une succession du Paléozoïque moyen-supérieur de part et d'autre de la zone de failles de Columbia River est compatible avec un déplacement de quelques kilomètres au plus. Cette succession paléozoïque est lithologiquement différent des groupes de Lardeau et de Milford exposés à l'est du Batholithe de Kuskanax. La transition entre les deux successions pourrait être une charnière de bassin, le foyer d'une interdigitation sédimentaire ou une faille synsédimentaire ou post-sédimentaire.

INTRODUCTION

The Columbia River fault zone (Read and Wheeler, 1976; Read, 1979; Read and Brown, 1981; Lane, 1984) in the southern Canadian Cordillera has been interpreted as a crustal-scale Cenozoic structure having tens of kilometres of down-to-the-east hanging-wall displacement and defined by a mylonite zone hundreds of metres thick (e.g. Parrish et al., 1988). Recent fieldwork, however, revealed that a coherent regional succession can be traced from footwall to hanging wall across the Columbia River fault zone (e.g. Thompson, R.I., Glombick, P., Daughtry, K., and Erdmer, P., LITHOPROBE-SNORCLE-Cordilleran Tectonics Workshop, Pacific Geoscience Centre, Sidney, British Columbia, 2001; Thompson, R.I., Glombick, P., Acton, S., Heaman, L., Freidman, R., Daughtry, K., Erdmer, P., and Paradis, S., unpub. paper presented at LITHOPROBE-SNORCLE-Cordilleran Tectonics Workshop, Pacific Geoscience Centre, Sidney, British Columbia, 2002; Lemieux et al., 2003). The succession of middle Paleozoic quartzite, marble, and schist has been traced from the Adams Lake–Chase area (i.e. western margin of Monashee Complex) eastward and southward to the western margin of the Kuskanax Batholith along Upper Arrow Lake, a distance of more than 150 km. The present project, initiated during the summer of 2002 (*see* Lemieux et al., 2003), addresses the stratigraphic, structural, and metamorphic relationships along the Columbia River valley as a means of assessing the location, geometry, and magnitude of displacement on the Columbia River fault zone. This report presents the results of geological mapping in 2003.

Mapping in 2002 (Fig. 1) had demonstrated the continuity of mid-Paleozoic rock units across the Columbia River fault zone, thereby limiting east-side-down displacement to about 1 km or less (Lemieux et al., 2003). Fieldwork in 2003 extended detailed coverage north of Nakusp and around the northern boundary of the Kuskanax Batholith to Trout Lake (Fig. 1). Fieldwork west of Upper Arrow Lake was also extended north and west, into the Arrow Park (Mosquito Lake) area. The objective was twofold: 1) to determine whether the Columbia River fault zone between Nakusp and Mount Sproat remains a steeply dipping, brittle normal fault with limited displacement, and 2) to assess stratigraphic linkages between supracrustal rocks of the Monashee Complex (e.g. Reesor and Moore, 1971) west of the Kuskanax Batholith and the Hamill Group–Badshot Formation–Lardeau Group–Milford Group–Kaslo Group succession east of the batholith (e.g. Fyles and Eastwood, 1962; Klepacki and Wheeler, 1985).

Principal results of this study are as follows: 1) Field relationships in and around the Columbia River fault zone along Upper Arrow Lake and in the vicinity of Mosquito Lake (previously informally known as 'Arrow Park Lake') show the existence of several moderately to steeply dipping, brittle fault zones with limited displacement. 2) Rock successions that track around the south-plunging end of the Monashee Complex also occur east of Upper Arrow Lake, across the Columbia River fault zone. This stratigraphic continuity is incompatible with crustal-scale displacement along the fault zone south of Galena Bay. 3) The Paleozoic stratigraphic succession mapped in the Upper Arrow Lake area is both older and lithologically distinct with respect to the Milford and Kaslo groups east of the Kuskanax Batholith; the nature of the transition zone between the two successions, however, requires additional investigation.

STRATIGRAPHY

Upper Arrow Lake area

The authors have divided the stratigraphic succession along Upper Arrow Lake into 6 units (*see* Lemieux et al. (2003) for a complete description): unit 1 is stratigraphically lowest and includes hornblende-biotite schist and paragneiss (±sillimanite±kyanite±garnet±muscovite) with minor calc-silicate and amphibolite, and is considered a southeastward extension of a Proterozoic cover succession belonging to the Monashee Complex ("mantling gneiss" succession of Reesor and Moore (1971)). Its base is not exposed and its thickness is unknown. Unit 2 consists of a distinctive diopside-bearing, calcareous quartzite with minor calc-silicate and marble; it varies from 10 m to more than 200 m in thickness. On the basis of regional correlation with the Chase Quartzite of Jones (1959), unit 2 has been interpreted to be Devonian (Thompson, R.I., Glombick, P., Acton, S., Heaman, L., Freidman, R., Daughtry, K., Erdmer, P., and Paradis, S., unpub. paper presented at LITHOPROBE-SNORCLE-Cordilleran Tectonics Workshop, Pacific Geoscience Centre, Sidney, British Columbia, 2002; *see also* Lemieux et al., 2003). The contact between units 1 and 2 is locally well exposed, for example on Saddle Mountain (*see* Fig. 1 for location), it is a layer-parallel, sharp surface separating rocks in which schistosity is parallel (*see* Fig. 3b *in* Lemieux et al., 2003). From these characteristics and map patterns, the contact is interpreted to be a transposed stratigraphic unconformity; a structural contact, however, cannot be ruled out. The upper contact of unit 2 is gradational with quartz-feldspar-biotite schist (±muscovite and rarely sillimanite and garnet) and minor calc-silicate and amphibolite of unit 3. Unit 3 also includes a distinctive and regionally extensive staurolite-bearing schist a few hundred metres above the contact with unit 2. Although the exact thickness of unit 3 is unknown, it is estimated to be 400 to 500 m. Unit 4 consists of limestone which is poorly exposed and likely discontinuous; its contact with adjacent units remains elusive. Unit 5 (Kaslo Group, e.g. Klepacki and Wheeler, (1985)) is at least 500 m thick and comprises fine-grained, massive greenstone with local pillow structures. Unit 6 (Slocan Group of Little (1960)) unconformably overlies unit 5, and includes fine-grained, dark grey phyllite, argillite, slate, and silstone, and its thickness is estimated to be over 1500 m. This unit is locally overlain by augite porphyry flows correlated with the Rossland Group (Little, 1960), referred to here as unit 7. On the basis of map patterns and field observations, no evidence exists to suggest that the stratigraphic section in the Upper Arrow Lake area could be locally or regionally overturned.

Additional exposures of diopside-bearing, calcareous quartzite (unit 2) and staurolite-bearing schist (subunit of unit 3) were mapped west of Saddle Mountain and near Mosquito

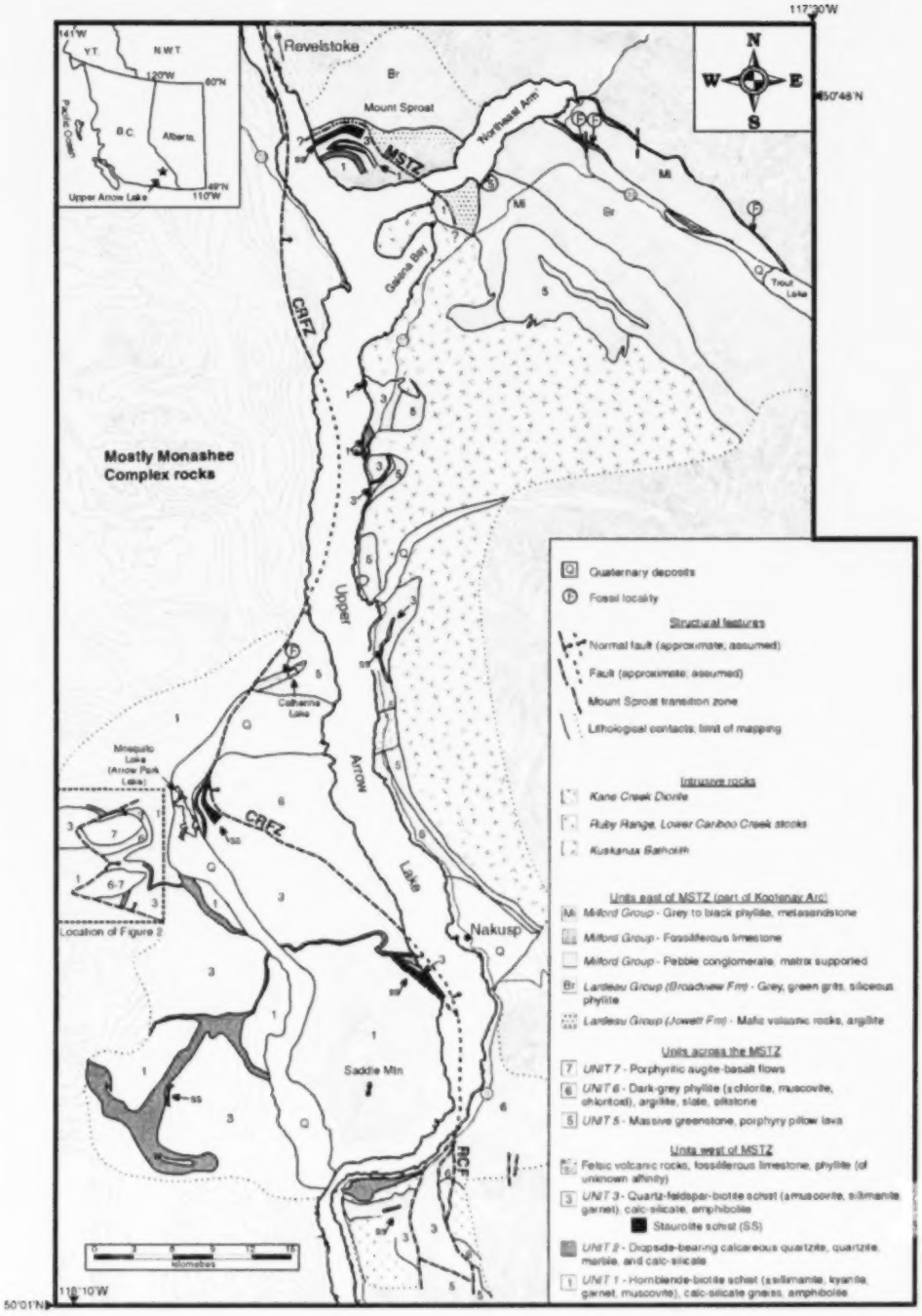

***Figure 1**. Geology of the Upper Arrow Lake area. CRFZ, Columbia River fault zone; RCF, Rodd Creek Fault; MSTZ, Mount Sproat transition zone. Inset: Location map of the Upper Arrow Lake area. Topographic contours from Canada NTS 1:250 000 scale Vernon and Lardeau maps.*

Lake (Fig. 1, 2), providing increased control of the distribution of units 2 and 3. The authors also examined a carbonaceous phyllite succession near Catherine Lake (unit S_3 of Reesor and Moore (1971); *see* Fig. 1 for location), in which a fossiliferous limestone (Famennian-Tournaisian, Orchard (1985); fossil locality shown in Fig. 1) and a distinctive, muscovite–quartz-eye schist, interpreted as an altered felsic volcanic unit, occur. This succession stratigraphically overlies unit 3 schist and is, in turn, overlain by unit 5 greenstone. Mapping along the eastern side of Upper Arrow Lake demonstrated stratigraphic correlation across the Columbia River valley. Exposures of hornblende-biotite schist and calc-silicate gneiss (unit 1); diopside-bearing, calcareous quartzite (unit 2); and staurolite-bearing schist (unit 3) occur along the eastern shore of Upper Arrow Lake between Nakusp and Galena Bay, and on Mount Sproat near the north end of the lake (Fig. 1). Matching rock units are exposed west of Upper Arrow Lake. This continuity of a regional stratigraphy precludes significant stratigraphic omission. Structural offset of a polyphase-deformed stratigraphic succession across the Columbia River valley at this latitude remains difficult to estimate, but is unlikely to exceed a few kilometres. That interpretation supports the conclusion of an earlier study in which displacement on a brittle Columbia River fault zone was interpreted to die out at Galena Bay (Lane, 1984).

Trout Lake area

The early Paleozoic (and possibly younger) Lardeau Group (Fyles and Eastwood, 1962) includes (in ascending order): 1) dark-grey and green phyllite of the Index Formation, 2) grey to black siliceous argillite of the Triune Formation, 3) massive grey quartzite of the Ajax Formation, 4) dark-grey to black siliceous argillite of the Sharon Creek Formation, 5) mafic volcanic rocks and argillite of the Jowett Formation, and 6) grey and green grit and phyllite of the Broadview Formation. The Lardeau Group conformably overlies Lower Cambrian rocks of the Hamill Group and Badshot Formation. Parts of the Triune, Ajax, Sharon Creek, and Jowett formations are present in the study area; no exposures of the Index Formation were observed; rocks of the Broadview Formation occur widely. The Broadview Formation is distinguished in the field by its dominant, rounded, black quartz grit unit and ubiquitous foliation-parallel, quartz-rich veinlets and lenses in the phyllite (Fig. 3a).

The Mississipian Milford Group unconformably overlies the Lardeau Group (Fig. 3b; e.g. Klepacki (1983)). In the study area, the Milford Group includes a pebble-conglomerate at its base, with clasts ranging from a few millimetres up to 15 cm across. The clasts include quartzite, grit, limestone, granitoid rocks, chert, greenstone, and mafic volcanic rocks in a muscovite-rich, phyllitic matrix. The conglomerate is at least 100 m thick. A bluish-grey, massive limestone, commonly featuring crinoid stems and corals overlies it. Northeast of the study area, near Comaplix Mountain, equivalent carbonate units in the undifferentiated Milford Group have yielded Visean conodonts (Orchard, 1985). In the Poplar Creek area to the southeast (along strike), similar bluish-grey limestone grades into massive, white, crystalline limestone with indistinct bedding (unit 14 *in* Read, 1973), overlain by a thick succession of mainly noncalcareous grey to black phyllite with minor metasandstone (unit 17 *in* Read, 1973). Phyllite of the Milford Group lacks the prominent foliation and quartz lenses that typify the Broadview Formation and appears less strongly metamorphosed. These two successions have been interpreted as part of the pericratonic 'Kootenay terrane' and, as such, allochthonous with respect to the North American miogeocline (e.g. *see* Roback et al., 1994); stratigraphic affinities with the miogeocline, however, are suggested on detailed maps (Read, 1973; Klepacki, 1983). The appropriateness of the term 'Kootenay terrane' was rejected by Colpron and Price (1995) and the present authors similarly infer that the rocks have stratigraphic links with the miogeocline to the east.

At Tenderfoot Lake in the Poplar Creek map area, east of the study area, a distinctive diopside-epidote-bearing calcareous quartzite outcrops as lenses (unit 18 *in* Read, 1973). It is lithologically identical to diopside-bearing, calcareous quartzite along Upper Arrow Lake (unit 2 of this study) and stratigraphic correlation has been postulated (Thompson, R.I., Glombick, P., Daughtry, K., and Erdmer, P., LITHOPROBE-SNORCLE-Cordilleran Tectonics Workshop, Pacific Geoscience Centre, Sidney, British Columbia, 2001).

STRUCTURAL GEOLOGY

Columbia River fault zone

South of Nakusp, the Columbia River fault zone coincides with Hyndman's (1968) Rodd Creek Fault (Fig. 1). Mapping of that area in 2002 by the present authors showed that offset at surface across the fault zone is 1 km or less. Work in 2003 extended to the northwest near Mosquito Lake, where the Columbia River fault zone has been interpreted to define the base of two Late Triassic to Middle Jurassic outliers (*see* Fig. 1, 2; e.g. Read and Brown (1981)). The present authors also examined the surface trace of the fault zone between Mosquito Lake and Upper Arrow Lake, where a sliver of hanging wall rocks was previously mapped (e.g. Read and Brown, 1981).

The two outliers west of Mosquito Lake are composed of Late Triassic, biotite-grade phyllite and of Middle Jurassic greenstone that overlie staurolite and garnet-grade, and locally sillimanite-grade schist and gneiss. Scarce outcrops of mylonitized marble and schist had been interpreted to indicate the base of klippen and the trace of the Columbia River fault zone (Read and Brown, 1981). Recent logging roads and timber clear cutting provided access to new exposures. Neither a thick mylonite nor zones of mylonite were observed, but instead exposures and zones of cataclastic rocks; most of these were restricted to the western part of each outlier (Fig. 2). The most continuous exposure defines a north-striking fault zone that dips moderately (less than 30°) to the east (Fig. 3c). This 2–3 m thick fault zone is characterized by fault breccia and dark gouge. It juxtaposes interlayered schist and calc-silicate of unit 3 in both the hanging wall and footwall.

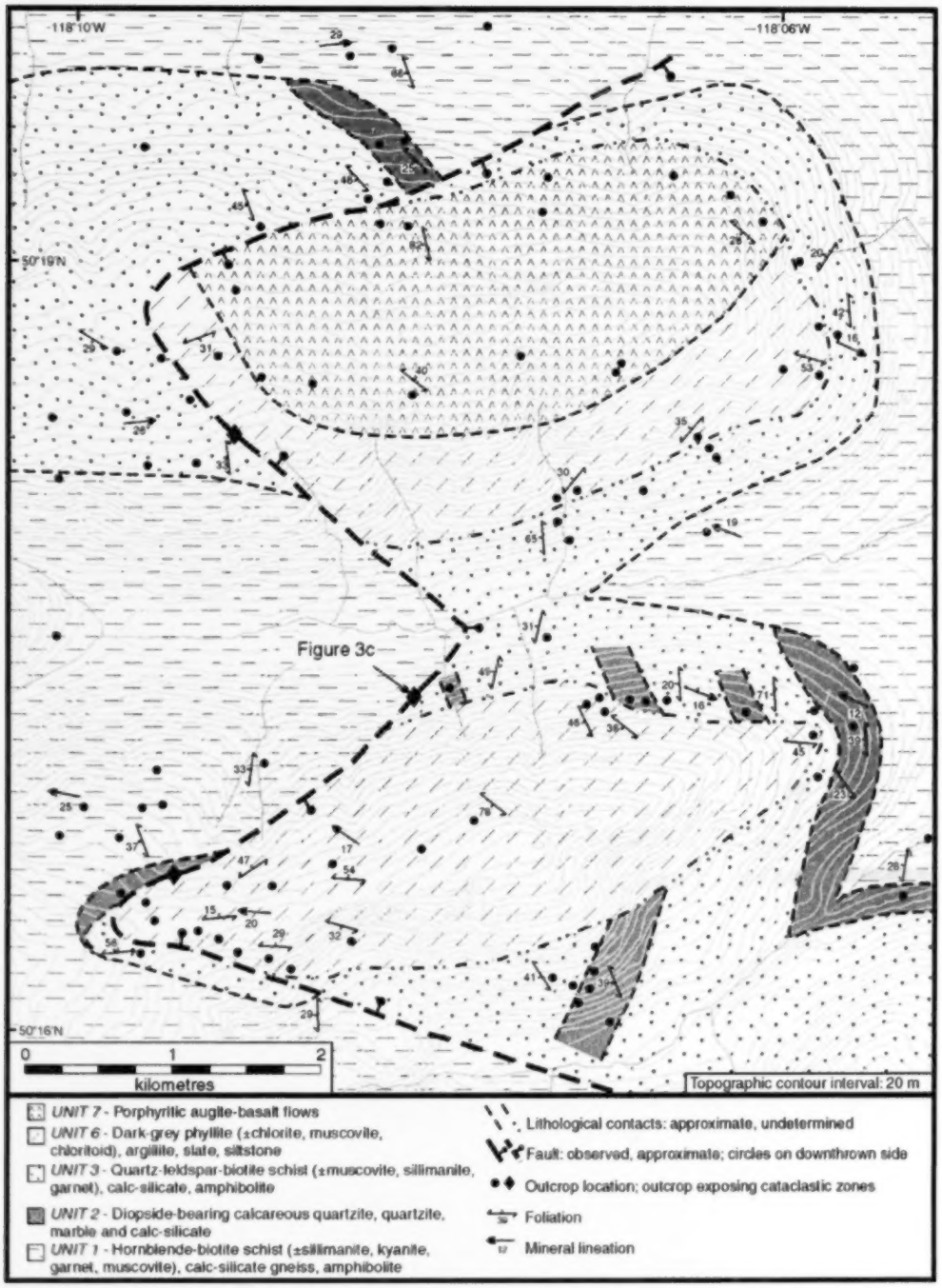
118°10'W
118°06'W
50°19'N
50°16'N
Figure 3c
0
1
2
kilometres
Topographic contour interval: 20 m
UNIT 7 - Porphyritic augite-basalt flows
UNIT 6 - Dark-grey phyllite (±chlorite, muscovite, chloritoid), argillite, slate, siltstone
UNIT 3 - Quartz-feldspar-biotite schist (±muscovite, sillimanite, garnet), calc-silicate, amphibolite
UNIT 2 - Diopside-bearing calcareous quartzite, quartzite, marble and calc-silicate
UNIT 1 - Hornblende-biotite schist (±sillimanite, kyanite, garnet, muscovite), calc-silicate gneiss, amphibolite
Lithological contacts: approximate, undetermined
Fault: observed, approximate; circles on downthrown side
Outcrop location; outcrop exposing cataclastic zones
Foliation
Mineral lineation

***Figure 2**. Geological map of two Mesozoic outliers west of Mosquito Lake (see Fig. 1 for location). Numbers refer to units described in the text.*

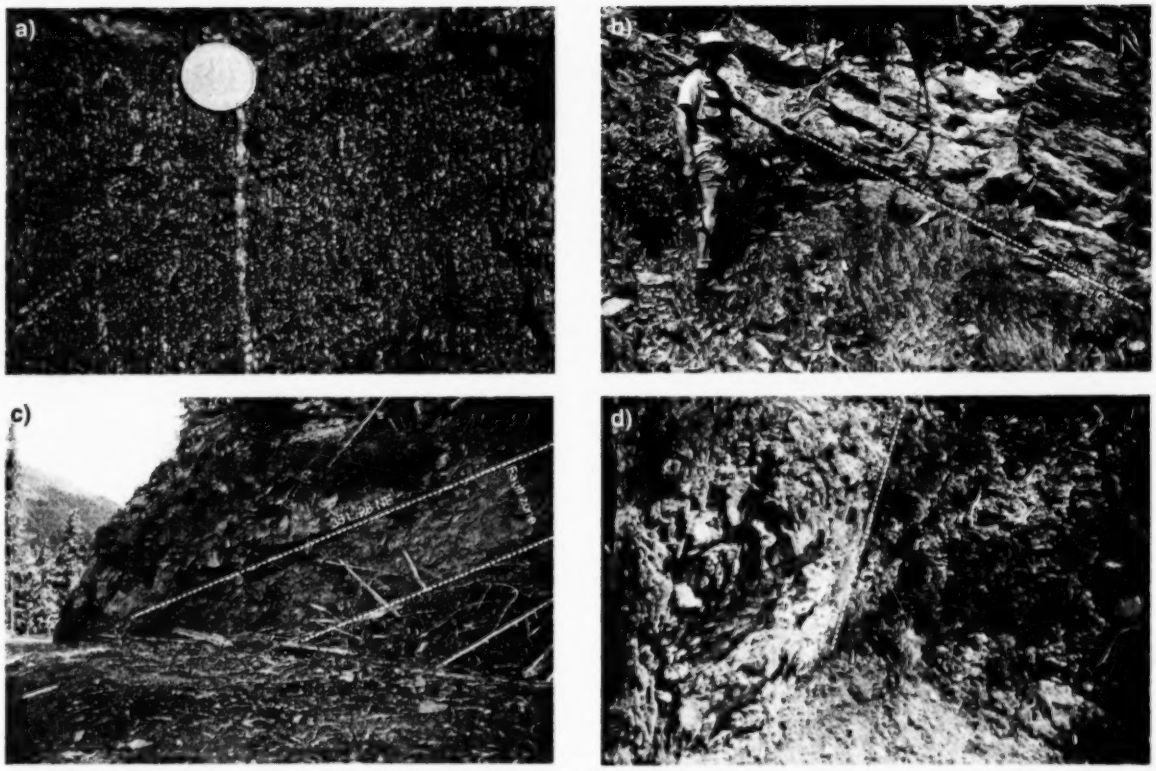

Figure 3. *a) Natural outcrop surface of part of the Broadview Formation (Lardeau Group) showing abundant black quartz clasts. Coin is about 1 cm across.* ***b)*** *Unconformity (dashed line) between limestone of the Milford Group and underlying green phyllite of the Lardeau Group. This exposure represents an overturned limb of a tight southeast-verging fold. Dashed line highlights the unconformity. View looking to the northwest.* ***c)*** *Cataclastic zone on the northern flank of the southern Mesozoic outlier. Fault zone is about 2–3 m thick. Dashed lines define the faulted zone. View looking to the northeast.* ***d)*** *Discrete and brittle fault plane in a cataclastic zone east of Arrow Park. Dashed line represent the orientation of the discrete fault plane. View looking to the southeast. A hammer (40 cm) is visible at the base of the rock face.*

Elsewhere around the outliers, no other outcrops expose the contact between the Mesozoic units and the underlying high-grade rocks. Many outcrops, however, occur close (<10 m) to the contact. Despite the marked metamorphic gradient across the contact, no evidence of increased strain was observed at the base of the Mesozoic rocks; although the contact surface remains poorly exposed, angular truncation of the dominant foliation across the boundary (*see* Fig. 2) suggests that the contact could be an original stratigraphic unconformity. The existence of a regional unconformity underlying Triassic rocks has been established in adjacent parts of the southern Cordillera (e.g. Read and Okulitch, 1977). If the contact was strongly tectonized, or was the locus of ductile flow, constraints imposed by the detailed mapping do not allow for a strain zone as thick (i.e. over 100 m) as described to the north for the Columbia River fault zone (e.g. Read and Brown, 1981); if the contact is regionally stratigraphic, the use of the term 'klippe' to define the two outliers (e.g. Read and Brown, 1981) obscures the original relationship. The origin of the steep metamorphic gradient across this contact remains elusive, as elsewhere beneath correlative Triassic rocks.

East of Mosquito Lake, sparse outcrops of cataclastic rocks were mapped (e.g. Fig. 3d). They expose moderately to steeply dipping, brittle fault zones with down-dip to oblique striations compatible with down-to-the-east hanging wall motion. Stratigraphic throw across the zones suggests small or insignificant displacement on a regional scale (e.g. *see* Lemieux et al., 2003).

DISCUSSION

The Columbia River fault zone has been described as a shallow to moderately east-dipping detachment with a strike length of about 200 km. North of Revelstoke, mylonite zones hundreds of metres thick have been interpreted to mark the locus of the fault zone (e.g. Read and Brown, 1981). In the Revelstoke area, Lane (1984) restricted the term "Columbia River fault zone" to a brittle structure that overprints a ductile mylonite zone (which he referred to as the "Monashee décollement"). To the south, the fault zone has been interpreted to extend as far as Scalping Knife Mountain, where it

was hypothesized to link with Hyndman's (1968) Rodd Creek Fault (Read and Brown, 1981). Estimates of down-to-the-east hanging wall displacement exceed 10 km (e.g. Read and Brown, 1981; Parrish et al., 1988). That amount of slip appears to be inconsistent with the constraints imposed by field relations on brittle structures south of Mount Sproat (*see also* Lane, 1984).

Significance of the stratigraphic succession

The supracrustal succession along Upper Arrow Lake consists of several kilometres of metamorphosed clastic and volcanic rocks. Its original stratigraphic thickness is unknown. Paleozoic to Lower Jurassic rocks east of Upper Arrow Lake were originally interpreted as part of the Quesnel and Slide Mountain terranes, thought to have been obducted onto the North American plate margin in the Middle Jurassic (Klepacki and Wheeler, 1985; Carr, 1991). West of Upper Arrow Lake, rocks were interpreted to include Late Proterozoic to Mesozoic amphibolite-facies rocks of the Shuswap metamorphic complex (e.g. Carr, 1991).

It appears, however, that most of the stratigraphic succession exposed along Upper Arrow Lake forms part of a newly identified, relatively thin (<1000 m) Middle Paleozoic succession of significant regional extent (*see* Thompson, R.I., Glombick, P., Daughtry, K., and Erdmer, P., LITHOPROBE-SNORCLE-Cordilleran Tectonics Workshop, Pacific Geoscience Centre, Sidney, British Columbia, 2001; Thompson, R.I., Glombick, P., Acton, S., Heaman, L., Freidman, R., Daughtry, K., Erdmer, P., and Paradis, S., unpub. paper presented at LITHOPROBE-SNORCLE-Cordilleran Tectonics Workshop, Pacific Geoscience Centre, Sidney, British Columbia, 2002; Thompson et al., 2003; Lemieux et al., 2003). As noted above, that succession, which overlies Proterozoic paragneiss and schist, includes at its base a distinctive calcareous quartzite unit which the present authors have correlated with the Chase Quartzite of Jones (1959), that is overlain by a pelitic schist unit which the present authors have correlated with the Silver Creek Formation of Jones (1959; Thompson, R.I., Glombick, P., Acton, S., Heaman, L., Freidman, R., Daughtry, K., Erdmer, P., and Paradis, S., unpub. paper presented at LITHOPROBE-SNORCLE-Cordilleran Tectonics Workshop, Pacific Geoscience Centre, Sidney, British Columbia, 2002; *see also* Lemieux et al., 2003). The stratigraphy can be mapped from west of the Okanagan valley into the present study area and eastward across Upper Arrow Lake, a distance of more than 100 km, where it is truncated by the Middle Jurassic Kuskanax Batholith and coeval intrusions. The occurrence of similar stratigraphy on both sides of Upper Arrow Lake implies exposures of comparable crustal levels and is inconsistent with a crustal-scale (>10 km), dip-slip displacement along the Columbia River fault zone south of Galena Bay.

Approximately 7 km north of Galena Bay, near Mount Sproat (*see* Fig. 1), the Middle to Upper Paleozoic succession is juxtaposed against rocks mapped as part of the Kootenay Arc (e.g. Klepacki and Wheeler, 1985). In the Trout Lake area north of the Kuskanax Batholith, grit and phyllite of the Lardeau Group are unconformably overlain by clastic rocks of the Milford Group. The Middle to Upper Paleozoic succession mapped along Upper Arrow Lake, although occurring east of the lake, is lithologically distinct from rocks near Trout Lake, i.e. the "Upper Arrow Lake" succession does not occur east of Mount Sproat. The transition between it and the Lardeau Group occurs on Mount Sproat, and is informally termed the Mount Sproat transition zone (Fig. 1). To the south, the transition is truncated by the Kuskanax Batholith. The transition could be a basinal hinge or the locus of depositional interfingering, or a fault of syndepositional or postdepositional origin. Future mapping will focus on its nature.

In summary, recent structural and stratigraphic constraints show the presence of distinctive Paleozoic rock units on both sides of Upper Arrow Lake, suggesting a few kilometres, at most, of stratigraphic offset across the Columbia River fault zone to the south of Galena Bay. Moreover, exposures of cataclastic rocks in the study area are compatible with the existence of several, moderately to steeply dipping, brittle, small fault zones, but not of a zone of mylonite that would be several hundreds of metres thick and the locus of large displacement. The hypothesis that the Columbia River fault zone is a crustal-scale detachment is not viable in the Upper Arrow Lake area; displacement on the fault zone, however, appears to increase north of Mount Sproat (e.g. *see* Lane, 1984).

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